Pipes to Earth's subsurface: The role of atmospheric conditions in controlling air transport through boreholes and shafts

Letter of response:

Reviewer 3:

This paper, after a noteworthy revision, could be a useful contribution to the literature on air transport and borehole-atmosphere exchanges. This manuscript studies the air transport between three borehole types using temperature and pressure gradients and using the water vapor as tracer of air flow. Levintal et al. found that the main mechanism driven the air transport depend on the geometries, where changes in pressure induce more transport in narrow boreholes and temperature differences induce more transport in wide-diameter boreholes.

We would like to thank the anonymous reviewer for his comments and fruitful review. A detailed response for each comment is presented below in blue font.

My major comment to this paper is that the authors are studying the air transport neglecting the air composition to estimate the air mass buoyancy. The virtual temperature (Tv) is the temperature at which dry air would have the same density as the moist air, at a given pressure. In other words, two air samples with the same Tv have the same density, regardless of their actual temperature or relative humidity. Levintal et al are measuring the relative humidity in the external and internal air, therefore they would be estimate the virtual temperature to study the buoyancy.

The authors mention that they found around 2000 ppm of CO_2, however they don't show the CO_2 pattern in any graph and the CO_2 sensors are not described in methodology. I suggest showing the data as supporting information and discuss the possible influence in the air composition and its buoyancy.

We fully agree with both of the comments above, and also mentioned by Reviewer 1 (Prof. Kowalski). We revised our MS accordingly:

(1) A summary of the virtual temperature concept (*Tv*) was added to the introduction: "Although air density depends mainly on temperature, it is also depend on the air humidity, and to a lesser degree on the air's gas composition (Kowalski and Sánchez-Cañete, 2010). Integration of these three effects (temperature, relative humidity, and air composition) into a single parameter named virtual temperature (*Tv*) was proposed by Sánchez-Cañete et al. (2013)…. For a given altitude level, the *Tv* differences will determine the onset of TIC." (Page 2, lines 20-27).

(2) In figures 2, 6, and 7, the data are now presented as a function of *Tv* rather than T, according to Sánchez-Cañete et al. (2013).

We note that due to the fact that we didn't have continuous CO_2 measurements in this study, the *Tv* within the boreholes was calculated using the T and RH continuous measurements with a constant CO_2 concentration according to preliminary results that we obtained in a two-week period during the 2017 winter season (~2000 ppm) (CO_2 sensor type – IRGAs GMD-20, Vaisala, Finland). Obviously, the CO_2 concentration varies throughout the day and seasonally within the boreholes; however, we think that this is a reasonable choice because we know from these two weeks of measurements that the CO_2 inside the borehole did not increase above 2000 ppm, and the values are relatively low compared to other underground cavities such as caves (e.g., Denis et al., 2005; Guillon et al., 2015). In addition, the CO_2 changes are only the third parameter in importance after temperature and RH for air density convection. Therefore, we believe that this is a reasonable assumption.

We also decided to delete the paragraph dealing with CO_2 emission in section 3.5 due to the scant CO_2 measurements that were available for us.

Minor comments (line/page):

1-5/3: How far are both sites? Could you include coordinates?

The distance between the sites was ~60 km. We added this information to the Materials and Methods section: "The distance between these sites is ~60 km." (Page 3, line 12).

11/3: Edit "42".

Done.

30/3: It's not clear how many sensors do you have and their positions? Please add more information and include this information in Fig 1b.

We added a sentence to the figure caption that describes the sensor location: "The sensor's location within the *shaft* included four thermocouples at depths of: 0, 6, 18, and 24 m and two RH-temperature sensors at the lower part of the *shaft* at its connection point to the cavity (27 m depth)." (Page 17, Lines 3-4).

8/4: delete "An example of"

Done.

13/4: the number 6050 will be 6048 (6 measurements/h*24h/day*42day)

Thank you, we missed calculated this number, and we changed it to 6048.

14-15/4: provide the % of relative humidity for 12 and 27 separately. In figure 1 and figure S1 I can see that during the whole period the relative humidity is always higher at 12m than at 27m, does that make sense?

We agree that this is not as expected. The differences are on the scale of a few percentages, which according to the manufacturer are close to the accuracy limit of the sensor (~±1 %). Also, from previous studies, we know that the sensors can drift a few percentages when they are under high RH for long periods of time. Therefore, to be more on the "safe side", we changed the comparison to values of RH> 90% and from 95%. The sentence was changed accordingly to: "From the overall 6048 measurements (42 days) at 12 and 27 m, 79 and 76 % of the RH values were above 90 %, respectively. The remainder of the measurements were no lower than a minimum of ~50 % RH (Fig. S1 – supporting information)" (Page 4, Lines 22-24).

9/7: Could it be because the max-min variation in temperature is higher in the shaft than in the borehole?

We agree, and this can further indicate that the barometric pumping effect on the air transport is greater in the shaft compared to the borehole; therefore, the max–min temperatures within the shaft are higher than the borehole (i.e., the atmospheric daily temperature fluctuations of air has greater effects on the shaft air than the borehole air).

24/7: could you provide some analysis (as a simple R^2) to prove that the correlation AH-Temperature is higher than AH-pressure?

While preparing this manuscript, we tried different statistical analyses to compare between both correlations. We found no compatible R^2 analysis that could be implemented with our results. We are now working on a new study in this field in which we are developing the use of more complicated statistical tools, mainly Fast Fourier Transform and Cross-correlation to correlate between atmospheric forces and airflow within boreholes.

3-5/8: I can see in Figure 7 that negative values on dPatm/dt increase the RH at 10m. During the days 22-24 probably the atmospheric pressure was changing from low to high pressure and for this reason the negative values on dPatm/dt were much lower. Would be useful if you show the atmospheric pressure value in a second Y-axis in Fig 7, panel 4.

Following a comment from Reviewer 1, the time series of this figure was changed to April 2017; thus, we can compare between similar seasons at both locations (spring season). However, we found this comment useful regardless of the specific day, and therefore we decided to add the Patm as an additional y-axis in panel 4 here (Fig. 7) and also in Fig. 2.

5-end/11: In your conclusions, you would remark that these conclusions were carried out only with data during 42 days in the shaft, 4 days in the borehole and 7 days in the large-diameter borehole, therefore, in the future we need investigate during longer periods,... :because for example in the case of the CO2, you found 2000 ppm in spring, but commonly the maximum values of CO2 are reached in summer/fall and therefore they could affect to the buoyancy.

The problematic generalization of our conclusions was also commented on by the other reviewers. We extended the large-diameter borehole data to the spring season, but unfortunately, we still don't have complete one-year results of the boreholes due to technical restrictions. We agree that this is a limitation in our study. We combined the comments from each of the reviewers and added this limitation in the conclusions section: "…This mechanistic explanation was validated using the winter and spring season's dataset. Although we show that theoretically the transport mechanism observed for winter and spring should hold, with reduced significance, for summer and autumn, further data are needed to verify the theoretical calculation.” (Page 11, lines 26-28).

Figure 2: In the legend “cavity air” is the Lower boundary, isn’t it?

Yes, we changed it to “lower boundary” such that the definition will be consistent in all the figures. Thank you.

2-3/17: delete “representative”

Done.

4/17: change from “black dashed line in 3” to “…in panel 3”

Done.

Figure 7: increase the scale on panel 1 because the air temperature during the day 25 is chopped, and also move the legend box.

As mentioned above, the time series of this figure was changed. In any case, the legend box was moved so it will not block the upper y-axis.